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Self-limiting Blowing Dust Mechanism

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Introduction

Historically the highest frequency of blowing dust days for the United States has occurred on the High Plains of Texas, centered on Lubbock (Changery, 1983). The synoptic climatology (i.e., the nature and distribution of the weather patterns) for blowing dust events across this region has been detailed by Wigner (1984) and Bernier (1995); see also Wigner and Peterson (1987). Data was available spanning about four decades for four stations: Amarillo NWS, Lubbock NWS, Reese AFB and Midland NWS. Unfortunately, with the closure of Reese AFB and the implementation of he automatic observational system (ASOS) by the National Weather Service, the continuity of the blowing dust data set has been broken.

For the four reporting stations there are significant differences in the dust source regions and also variations in the importance of possible high-wind generating mechanisms (e.g., strong cold fronts, deep cyclones, thunderstorm outflows etc.). The greatest dust frequency has been recorded in the center of the region at Lubbock NWS and Reese AFB (about 20 km from Lubbock in a more rural location); for these sites about 50% of the blowing dust hours occur triggered by the daytime mixing down of higher momentum air.

It is typical that the dry, cloudless air allows for substantial nighttime radiational cooling and the establishment of a strong but shallow surface-based temperature inversion. Due to the relatively low latitude (~33N), strong solar heating after dawn leads to a dry convectively unstable layer which evolves upward from the surface; this most often eventually eliminates the inversion. Thereafter, convective mixing proceeds rapidly to greater heights, with compensating downward motion transporting the winds with dust-raising potential to the ground. The greatest effect occurs during the winter. During this season, cloudiness is a minimum, the winds overhead are most vigorous and the ground cover is at a minimum.

There are at least two factors which can limit or curtail the heating responsible for the mixing-down process: cloudiness (either advected from elsewhere or generated by the mixing in situ) and/or dust raised by the winds. This paper considers a model for the self-limitation of the blowing dust event due to the increasing aerosol load in the atmosphere.

Clear-air Model

For the daytime convective modification of the lower atmosphere, Carson (1968) presented an analytic model which can be adapted to include the effect of the blockage of solar heating due to airborne dust. The formulation uses as input the initial vertical profile of the atmosphere, $T(z)$ or $\theta(z)$, and the time variation of the surface heating, $H(0, t)$. One of the key products of interest is the depth of the mixed layer as a function of time, $h(t)$.

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The one-dimensional (height), time-dependent heat equation is integrated over the depth of the mixed layer, incorporating the heating contributions both from the earth's surface, as well as the reservoir of potentially warm air aloft.

The heat equation is expressed in terms of the individual change of potential temperature, θ; changes are brought about by the vertical flux of sensible heating. In the decomposition of the total derivative of θ into the local time change and the vertical advection, allowance is made for large-scale vertical motion, $w(z)$:

$$\partial H/\partial z = -\rho c_p\left[\partial\theta/\partial t + w\partial\theta/\partial z\right].$$

The simplest initial situation has a surface-based temperature inversion with a constant lapse rate of θ surmounted by a deep stable layer with a different constant lapse rate. Once heating begins, a surface-based layer with constant θ evolves; a very shallow superadiabatic layer near the ground is ignored.

With the assumption that the stable air layer above the mixed layer is dominated by a linear lapse rate, γ, then the vertical motion is constrained to vary linearly with height; the constant of proportionality, β (subsidence parameter), is thus equivalent to the horizontal convergence (or divergence) of the upper layer.

A major element is the parameterization of the heat brought into the mixed layer from the layer above, $H(h, t)$; it is taken as proportional to the surface sensible heat flux:

$$H(h, t) = -AH(0, t)$$

where A is taken to lie between zero and one. This allows the formulation of the governing differential equation for the mixed layer depth:

$$dh^2/dt + 2\beta h^2 = 2[H(0, t) - 2H(h, t)]/\rho c_p\gamma(t).$$

The resulting solution for the depth of the mixed layer is a function of the rate of subsidence aloft, and the time integral of the heating function and the lapse rate of the atmosphere aloft:

$$h^2(t) = h^2(0)\exp(-2\beta t) + 2\exp(-2\beta t) \int \exp(2\beta\tau)\left\{[H(0, \tau) - 2H(h,\tau)]/\rho c_p\gamma(\tau)\right\} d\tau.$$

The integral limits are from 0 to t; $h(0) = 0$ if the initial inversion extends to the surface.

If the heating rate is taken as a simple sine function of the time since sunrise

$H(0, t) = \mathit{H}\sin\Omega t$, where H and Ω depend on the latitude and time of year,

then an analytic solution results:

$$h^2(t) = \left\{2(1 + 2A)\mathit{H}/\gamma(0)(\beta^2 + \Omega^2)\rho c_p\right\}\exp(-2\beta t)[\exp(\beta t)(\beta \sin\Omega t - \Omega\cos\Omega t) + \Omega].$$

Typical solutions for most parameter selections yield an almost linear increase with time in the depth of the mixed layer for half a dozen hours or so, with a leveling off as the heat input diminishes. For sufficiently strong large-scale subsidence though, the mixed layer depth may begin to decrease even while heating is substantial.

Dusty Model

The vertical mixing induced by the daytime heating not only redistributes the potential temperature but also other properties: humidity, momentum and of course dust. The effect is to produce constant values of each parameter over the mixed depth. The temperature lapse rate becomes dry-adiabatic (i.e., constant potential temperature with height). For humidity mixing usually results in a large decrease in the surface mixing ratio and the relative humidity. For momentum there is usually an increase in surface wind speed, accompanied by a shift of direction becoming increasingly like that of the winds aloft. As the surface wind increases, once a critical speed is attained, dust will be raised and be lifted.

As the dust volume increases, sunlight – and the surface heating - will be reduced. For simplicity the decrease may be taken as proportional to the amount of dust in the air, D:

$$H'(z, t) = H(z, t) - cD.$$

Likewise the amount of dust may be taken as proportional to the square of the wind speed, v:

$$D \propto v^2.$$

If the initial wind profile increases linearly with height

$$v(z, 0) \propto z,$$

then integrating over the depth of the mixed layer, 0 to h(t), yields a time variation of the mean layer wind (which develops at the surface) proportional to the time variation of the square of the mixed depth, $h^2(t)$.

Reducing the assumed heating function by a term dependent on the square of the mixed depth in the governing differential equation allows the dust reduction factor to be combined with the subsidence term. The net effect is analogous to increasing the subsidence from aloft. This in turn limits and perhaps even reverses the growth of the mixed depth. The increased dust load then is a self-limiting development.

Discussion

For blowing dust events triggered by the mixing-down mechanism, the aerosol may be expected to fill the mixed layer with time. Whether dust is raised will depend of course on the availability of a dust source and therefore the direction of the wind. (In the recent years sources have become even more restricted due to the maintenance of ground cover throughout the year – the conservation reserve program.)

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In the near future it may be possible to monitor the growth of the mixed layer within blowing dust events using observational platforms at the West Texas Mesonet site by serial launches of rawinsondes and/or by means of the lower atmosphere sounder. (Actual aerosol measurements may be made from the 200 m meteorological tower. This data will provide a test of the model predictions of mixed layer growth, in clear conditions as well as with blowing dust.

Conclusions

A simple model has been presented for the time evolution of the surface-based mixed layer assuming that wind-generated dust reduces the surface heating. It is hypothesized that the dust loading will lead to a limitation of the mixed-layer growth in a manner analogous to the role of large-scale subsidence.

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